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TITLE NUCLEAR DYNAMICS OF BOUND ETA MESONS: ETA-MESIC NUCLEI AND MESIC COMPOUND-NUCLEUS RESONANCES

AUTHOR(S) L.C. Liu

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Los Alamos Los Alamos National Laboratory Los Alamos, New Mexico 87545

Nuclear Dynamics of Bound Eta Mesons: Eta-Mesic Nuclei and Mesic Compound-Nucleus Resonances

L. C. Liu

Los Alamos National Laboratory, Los Alamos, N.M. 87545, U.S.A.

INTRODUCTION

Only two forms of nuclear matter have been observed previously: ordinary nuclei and hypernuclei. The former are the bound systems of nucleons only; the latter are the bound systems of nucleons and a hyperon Λ or Σ. In this talk, I will discuss a possible new form of nuclear matter, eta(η)-mesic nuclei or bound systems of nucleons and an η meson. A comparison of the main features of these different kinds of nuclear matter is given in the following table:

	Usual Nuclei	Hypernuclei	η-Mesic Nuclei
constituents	nucleons	nucleons, Λ, Σ	nucleons, η
strangeness	0	-1	0
meson no.	0	0	1
av. exc.	0-30 MeV	~200 MeV	~540 MeV
force	NN	NN, ΛN, ΣN	NN, ηN

I will first review the theory of η-mesic nuclei and briefly describe the experiments designed to search for them. I will then present a theory of mesic compound-nucleus resonance. This latter theory allows us to study effects of η-nucleus bound states on other meson-nucleus reactions in which the η is not being observed.

THEORY OF ETA-MESIC NUCLEI

As we know, the structure of the η meson is still not fully understood. The simple SU(6) quark model cannot account for the mass difference between η and η' mesons. Studies of eta-nucleon interaction will provide useful information that might shed light on the structure of η. Because it is nearly impossible to produce an η beam, the nucleus is the only laboratory for η nucleon physics.

If the η-nucleus system can have bound states, then the study of ηN interaction will be greatly facilitated. This is because the discrete binding energies are, in general, much more sensitive than the (π,η) cross sections are to the details of the ηN interaction.

Indeed, various analyses of the $\pi N \to \eta N$ reaction indicate that the low-energy ηN interaction is attractive[1,2]. The most recent theoretical analysis is given by Bhalerao and Liu[1] who have developed a coupled-channel model to study simultaneously πN elastic scattering, $\pi N \to \pi\pi N$, and $\pi N \to \eta N$ reactions. This model is particularly suitable for calculating ηN interactions in a nucleus because it contains strong-interaction form factors and satisfies off-shell unitarity. The basic interactions of this model are shown in Figs. 1a to 1c, where α denotes the isospin-1/2 πN resonance. For c.m. energy, $\sqrt{s}$, between 1470 and 1600 MeV, only one such resonance has to be considered for each given meson-nucleon partial-wave amplitude; they are N*(1535) for the s-wave, N*(1440) for the p-wave, and N*(1520) for the d-wave amplitude.

The radial part of the ηN scattering amplitude is given by

$$\langle p'|T^{\alpha}_{\eta N,\eta N}(\sqrt{s})|p\rangle = \frac{g^2_{\eta N\alpha} v_{\eta N\alpha}(p',\Lambda_{\eta N\alpha}) v_{\eta N\alpha}(p,\Lambda_{\eta N\alpha})}{\sqrt{s}-m^{\alpha}_{B}-\Sigma^{\alpha}_{\pi\pi}(\sqrt{s})-\Sigma^{\alpha}_{\pi}(\sqrt{s})-\Sigma^{\alpha}_{\eta}(\sqrt{s})}. \quad (1)$$

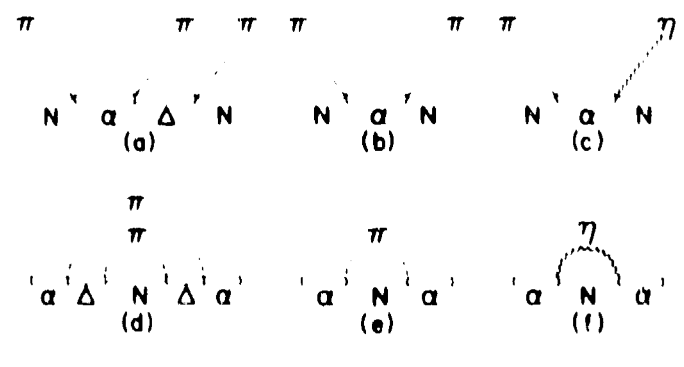

Fig.1. (a)-(c) Interaction matrix elements of the coupled-channel model; (d)-(f) Self energies of the resonance α.

In Eq.(1), $\sqrt{s}$ is the total c.m. energy and v is the strong-interaction form factor. The g and Λ are, respectively, the coupling constant and range parameter. The m_B^α and Σ^α are, respectively, the bare mass of and the self-energies of the resonance α. These self-energies arise from the coupling of the resonance to the $\pi\pi N$, πN, and ηN channels (Figs. 1d to 1f). The sum of the imaginary parts of Σ gives the resonance width Γ_α, while the sum of the bare mass and the real parts of Σ gives the resonance energy m_α, i.e.

$$m_B^\alpha + \Sigma_{\pi\pi}^\alpha + \Sigma_\pi^\alpha + \Sigma_\eta^\alpha = m_\alpha(\sqrt{s}) - i\Gamma_\alpha(\sqrt{s})/2 \ . \qquad (2)$$

We note that m_α and Γ_α are energy-dependent. The m_α, g, and Λ of the coupled-channel theory of Ref.1 are determined from fitting only the πN phase shifts. The theory is able to make a good prediction for the $\pi^- p \to \eta n$ differential cross sections. It also gives an ηN scattering length $a_0 = 0.28 + i\ 0.19$ fm, corresponding to an attractive s-wave ηN interaction.

Haider and Liu have constructed a first-order optical potential[3] for η-nucleus scattering, using the ηN interaction of Ref.1. They have noted: (a) after including the s-, p-, and d-wave ηN interactions, the η-nucleus interaction remains attractive at low energies; (b) although the strength of the ηN attraction is not sufficient to bind the η to a single nucleon, it can bind an η into a nuclear orbital in a nucleus having a mass number A > 10. In order to see how the size of a nucleus can help develop an η-nucleus bound state, let us examine the case with uniform nuclear density. In this latter case, the condition for the nucleus to have one s-wave bound state is simply[3]

$$9X > \mathrm{Re}(a_0) > X, \qquad (3)$$

where a_0 is the ηN scattering length and $X = \pi^2 R A^{-1}(1+m_\eta/m_N)^{-1}/12$ with m_η, m_N, and R being, respectively, the η mass, the nucleon mass, and the nuclear radius. The depth of the η-nucleus optical potential well is

$$V = -197.3\times(3Aa_0/2R^3)(1+m_\eta/m_N)(m_\eta+m_A)/(m_\eta m_A) \quad [\mathrm{MeV}], \qquad (4)$$

where $m_A \simeq Am_N$ is the mass of the nucleus, and the unit of the masses is fm^{-1}. In the following table, we give the bound-state conditions and the potential wells calculated with the a_0 given in Ref.1.

Nucleus	V [MeV]	9X [fm]	X [fm]
p	-5.5-i 3.7	11	1.23
^{6}Li	-8.9-i 6.0	2.5	0.26
^{12}C	-17-i 12	1.3	0.14
^{16}O	-19-i 13	1.0	0.11
^{40}Ca	-20-i 14	0.53	0.059
^{90}Zr	-24-i 16	0.29	0.032
^{208}Pb	-29-i 20	0.15	0.017

Using $Re(a_0) = 0.28$ fm and Eq.(3), we see there is one s-wave η-nucleus bound state for $10<A<90$ and two for $A>90$. This qualitative result has been confirmed by our detailed calculations that make use of realistic nuclear densities, and full ηN interactions. The calculated binding energies are shown in Fig.2. The calculated widths of the η-mesic nuclei range from ~7 MeV in ^{12}C, ~10 MeV in ^{16}O, to 20 MeV in ^{208}Pb (Ref.1), which are compatible with the imaginary parts of the equivalent square-well potential in the table. We emphasize that the coupled-channel analysis of Ref.1 fits the S11 πN phase shifts. Consequently, the a_0 used in our analysis is consistent with the decay width (~100 MeV) of the N*(1535) in free space. We thus conclude that once a bound state is formed, its width is mainly determined by the equivalent potential well and not by the free-space width of the elementary meson nucleon resonance.

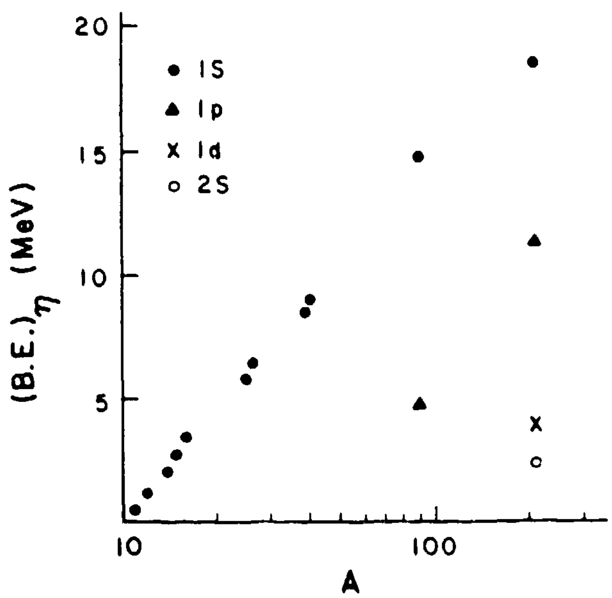

Fig.2. Calculated η binding energies.

We have mentioned in the beginning of this section that the η binding energy exhibits great sensitivity to the ηN interaction. To see this, we note that the η-nucleus interaction is proportional to the ηN scattering amplitude, $T^{N*}_{\eta N,\eta N}$, which depends nonlinearly on the coupling constant $g_{\eta NN*}$. The nonlinearity comes from the fact that in Eq.(1) the numerator and the self-energies in the denominator are all proportional to the $g^2_{\eta NN*}$. As a result of this dependence, the η-nucleus bound state can only exist for limited values of $g_{\eta NN*}$. In Fig. 3, I present the calculated s-wave ηN scattering length and the η binding energy in ^{15}O as a function of $g_{\eta NN*(1535)}$. The value determined in Ref. 1 is 0.77 (indicated by a vertical arrow). It gives $Re(a_0)=0.28$ fm, corresponding to an attractive interaction, and leads to a binding energy $B=2.4$ MeV and a half-width $\Gamma/2=5.2$ MeV for the η-mesic nucleus $^{15}_{\eta}O$. The B and Γ of $^{15}_{\eta}O$ increase rapidly with g. But, the bound state ceases to exist for $g>0.9$ because the nonlinear relation between $T_{\eta N,\eta N}$ and g^2 causes $Re(a_0)$, and hence, the η-nucleus interaction, to decrease for $g>0.85$. Therefore, bound state can only exist for g between 0.7 and 0.9. This narrow band of allowed values of g provides the possibility to extract quite accurately the ηN coupling constant from experiments.

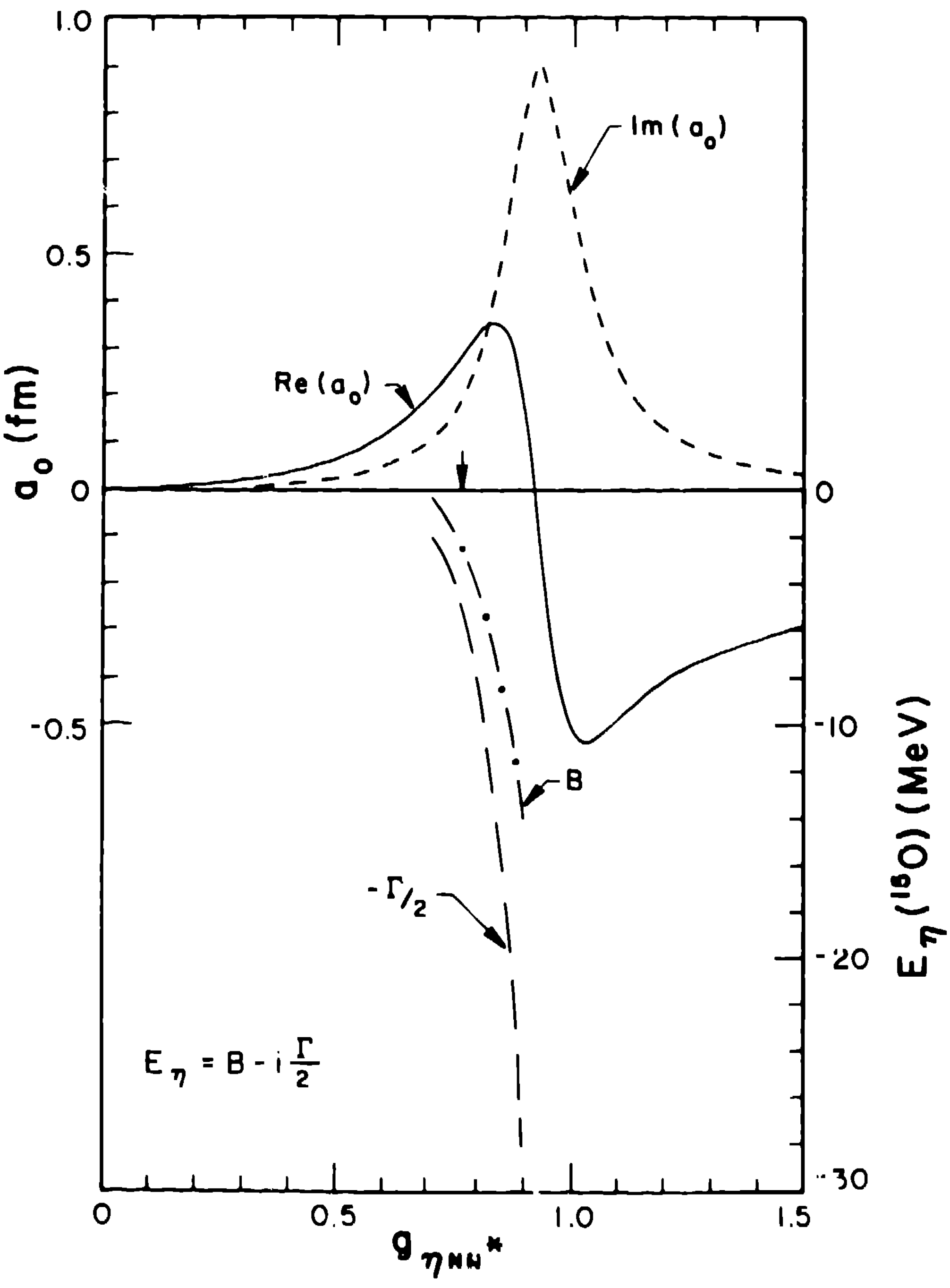

Fig.3 The ηN scattering length a_0, and the binding energy B and width Γ of $^{15}_{\eta}O$ as functions of the coupling constant $g_{\eta NN^*}$.

EXPERIMENTAL SEARCH

An experiment was performed at the AGS of Brookhaven National Laboratory [4]. The reaction used was

$$\pi^+ + {}^{Z}A \rightarrow p + [\eta + {}^{Z}(A-1)] = p + {}^{\eta}_{Z}(A-1).$$

If an η-mesic nucleus is formed, then a nearly monoenergetic peak will be seen in the outgoing proton spectrum at a well-defined energy. In particular, the peak that corresponds to the formation of a bound state after having ejected a least-bound neutron will be situated outside the kinematical limit of the quasi-free η production and by a distance equal to the binding energy of the η [5]. In Fig.4, I show a predicted proton spectrum for the $^{16}O(\pi^+,p)X$ reaction at pion momentum 740 MeV/c, where the abscissa is converted to the binding energy of η. Because the width of $^{15}_{\eta}O$ is ~10 MeV, the two peaks associated with the ejection of $1p_{1/2}$ and $1p_{3/2}$ neutrons cannot be separated in our calculations. The actual experiment was performed with 800-MeV/c incident π^+ on lithium, carbon, and oxygen. The outgoing protons were detected at 6^0 and 15^0. The preliminary results not only show evidence of quasifree η production in all the targets but also indicate the presence of peaks that can be associated with η-nucleus bound states in oxygen. Analysis is still in progress and final results will soon be reported elsewhere.

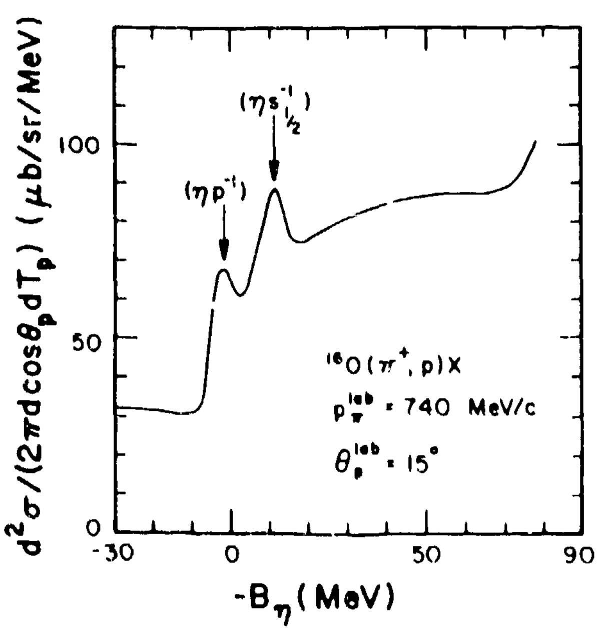

Fig.4. Calculated proton spectrum.

A second experiment will be carried out at LAMPF[6]. In this experiment one will detect in coincidence the ejected fast proton, and the decay product of the η-mesic nucleus. The corresponding reaction equation is

$$\pi^+ + {}^{Z}_{\eta}A \rightarrow p + {}^{Z}_{\eta}(A-1) \rightarrow p + \pi^- + p + X ,$$

where X denotes all the undetected particles. The π^- and the second proton are coming from the elementary process $\eta^{bound}+n\rightarrow\pi^-+p$. This triple coincidence measurement should greatly reduce the background events and provide information on the decay of an η-mesic nucleus.

OTHER EXPERIMENTAL POSSIBILITIES

Because the η meson can also be produced in high-energy pp collisions, it will be interesting to look for clues of η-mesic nucleus formation in proton-nucleus reactions. Because small η momenta are favorable to such formation, it is preferable that one works in an energy region where this kinematics can be realized. In Figs. 5 and 6, I present plots indicating the minimum η momentum that will be produced in various nuclear reactions.

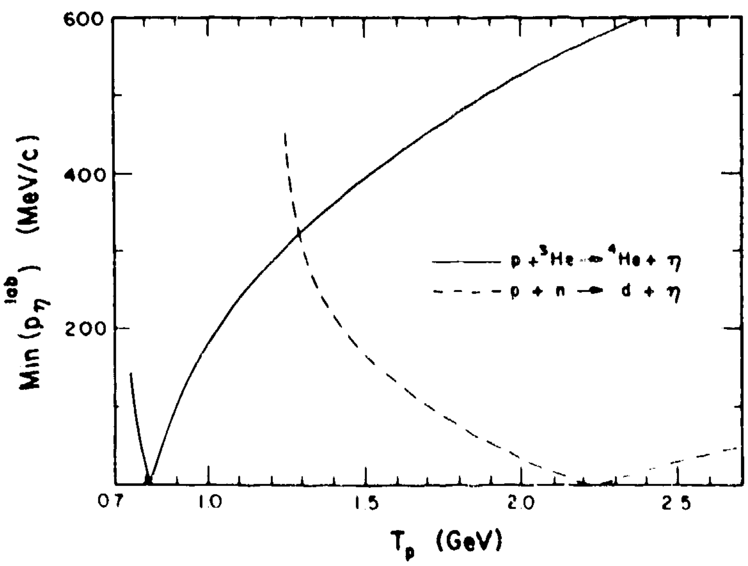

Fig.5 The lowest η momenta produced in the $p+n \rightarrow d+\eta$ and $p+{}^3He \rightarrow {}^4He+\eta$ reactions as a function of proton kinetic energy.

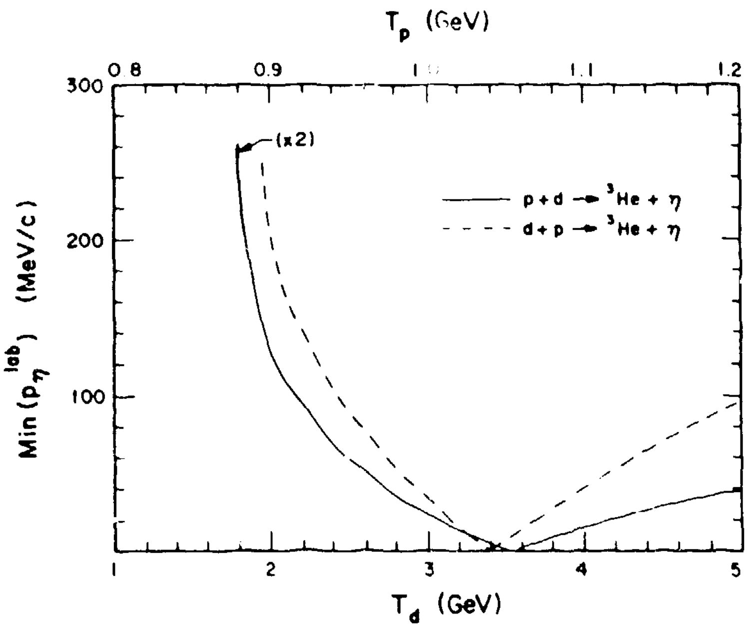

Fig.6 The lowest η momenta produced in the $p+d \to {}^3He+\eta$ and $d+\pi \to {}^3He+\eta$ reactions as a function of proton (upper abscissa) and deutron (lower abscissa) kinetic energies, respectively.

ETA-MESIC COMPOUND-NUCLEUS RESONANCE

The existence of η-nucleus bound states can also affect high-energy pion-nucleus reactions in which the η is not present in the final state. I will term this new nuclear phenomenon the mesic compound-nucleus resonance[7].

In this Symposium, many speakers have talked about pion-nucleus double charge exchange (DCX) reactions. Let us examine DCX from a new point of view. For pion kinetic eneries greater than 400 MeV, the η production channel is open in most nuclei. Consequently, the pion DCX reaction can proceed via the canonical $\pi^+ \to \pi^0 \to \pi^-$ processes, as well as via the new $\pi^+ \to \eta^0 \to \pi^-$ processes. Although the π^0 is in the continuum (Fig.7a), the η can either be in the continuum (Fig.7b) or in a nuclear bound state (Fig.7c). The DCX amplitudes associated with the continuum mesons have a relatively smooth energy dependence. On the other hand, the DCX amplitudes associated with the η-nucleus bound states, which manifest themselves as MESIC COMPOUND NUCLEUS states in the pion-nucleus channel, have resonances.

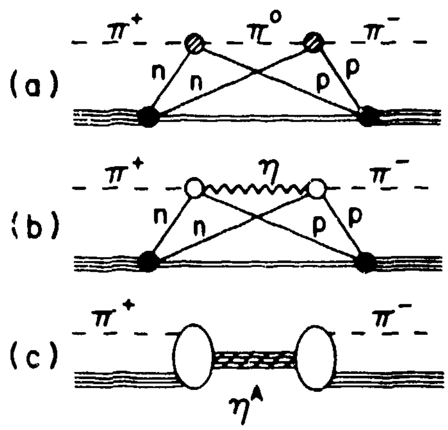

Fig.7 (a) The $\pi^+ \to \pi^0 \to \pi^-$ amplitude. (b) The $\pi^+ \to \eta \to \pi^-$ amplitude due to unbound η. (c) The $\pi^+ \to \eta \to \pi^-$ amplitude due to bound η.

The differential cross sections for the $^{14}C(\pi^+,\pi^-)^{14}N$(DIAS) reaction as a function of pion energy are shown in Fig.8. The dashed curves represent the contribution from nonresonant amplitudes alone. The solid curves include also the contribution from the resonant amplitude associated with the formation of η-nucleus bound states[7]. The interference of these amplitudes is responsible for the presence of a narrow resonance structure in the solid curves at pion kinetic energy ~419 MeV. The width is about 10 MeV, which reflects the width of the η bound state used in the calculations. We note that the fluctuation ratio $(\sigma_{max}-\sigma_{min})/\sigma_{average}$ is ~79% at momentum transfer q=210 MeV/c. At this momentum transfer, the cross section is ~100 nb/sr and is, therefore, measurable at existing meson facilities. It is further noteworthy that even if one assumes, because of possible multinucleon absorption of the η, that the width of the η-nucleus bound state could be as large as 40 MeV, one can still observe a fluctuation ratio of ~20% at q=210 MeV/c. In this respect, DCX studies provide an interesting alternative way to measure the width of the η-mesic nucleus.

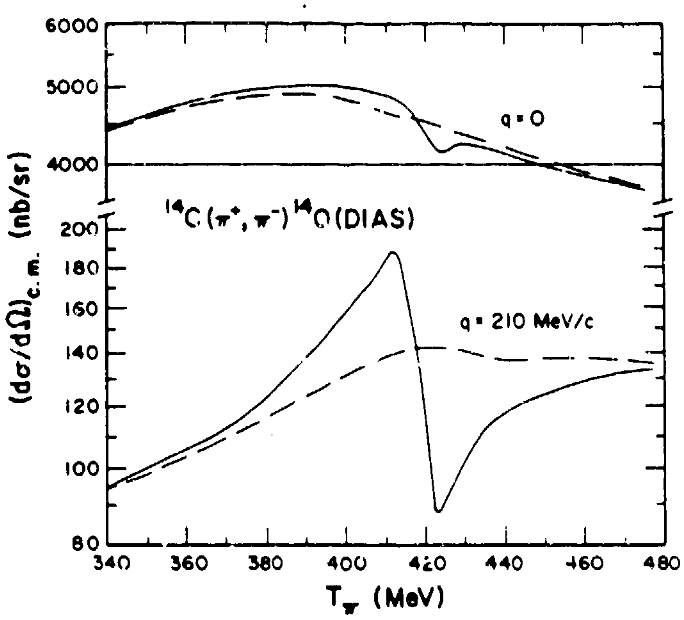

Fig.8 The calculated energy dependences of the $^{14}C(\pi^+,\pi^-)^{14}N$ reaction leading to the double isobaric analog state.

The η-mesic compound-nucleus effects are not limited to DCX reactions. For example, we can expect to observe these effects in (π,π') reactions leading to certain specific final states, for which the compound-nucleus amplitude is not small with respect to the usual nonresonant background amplitude. The study of the resonance pattern of the cross-section energy dependence will yield information on the relative phase between the resonant and nonresonant amplitudes and, hence, help to better understand both of these amplitudes.

SUMMARY

I have discussed the possibility of producing η-mesic nuclei by the use of pions. The binding energies of the η can be used to extract the ηNN* coupling constant in a nucleus. The existence of η-mesic nucleus can lead to a new class of nuclear phenomena, η-mesic compound-nucleus resonances. An awareness of this phenomenon could be beneficial to the analysis of nuclear reactions at energies above the η production threshold.

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